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TMD BATTLE MANAGEMENT*

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Abstract

A key objective of Theater Missile Defense (TMD) is to defend multiple assets spread over a wide theater, simultaneously threatened by numerous ballistic missiles. Battle Management, therefore, has to efficiently assign weapons and sensors to incoming threats to achieve intercepts, minimizing total leakage or total damage to assets. To analyze the TMD Battle Management problem to counter Theater Ballistic Missiles (TBM), threat propagation and radar models to predict antenna occupancy and track accuracy are developed. Interceptor flyouts are modeled to support candidate one-on-one fire control solutions. In addition, algorithms are developed for threat assessment, battle space-time analysis to determine shot opportunities satisfying system constraints, many-on-many weapon-target-sensor assignment to achieve optimality of the objective function, as well as engagement scheduling to determine the best intercept position and time. These models are then prototyped, integrated, and simulated in a rapid prototyping testbed. A number of attack and defense scenarios are simulated, and various measures of effectiveness determined, including leakage, damage to assets, accuracies of intermediate results, and computational performance. The results indicate sensitivity of weapon effectiveness on system constraints. Some of the key performance characteristics are graphically demonstrated.

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1. Introduction

The proliferation of TBM capabilities that go beyond the short-range has been on the rise during the recent past. These offensive missile capabilities have gone beyond the tactical and have migrated to the theater domain. And while theater missiles have ranges less than strategic (long-range) missiles, their intermediate ranges have widened the scope and complexity of the Theater Missile Defense problem which has gone beyond the tactical missile defense arena. To counter intermediate range theater missiles, radars and interceptors (upper-tier weapons) of corresponding ranges have been developed. With intermediate range threats, sensors, and weapons, TMD has, therefore, gone beyond the point defense environment of lower-tier weapons and has evolved into a 4-dimensional (4D) space-time problem, with multiple shoot-look opportunities. This, together with denser threat environments competing with interceptor inventories, has rendered the shoot-as-early-as-possible point-defense approach obsolete. Instead, the TMD problem has allowed the possibility of utilizing weapon assignment approaches that are more optimal than the typical point defense methods. Thus, to counter the intermediate ranges of theater threats, both the sensor and weapon have been upgraded to corresponding ranges, which has made the Battle Management problem more complex. This, then, has raised the possibility, albeit the need, for more robust techniques to solve the weapon-target assignment and related problems to achieve greater overall weapon system effectiveness.

Therefore, to analyze the overall TMD Battle Management problem with some degree of realism, the weapon-target assignment or Engagement Planning, as well as the Engagement Scheduling problems must be analyzed in an integrated fashion using realistic models of the threats, sensor, and weapon, which are described in section 2. Software prototypes for key algorithms are developed, tested, integrated, and simulated in a rapid prototyping testbed to assess the engineering performance (such as measures of system effectiveness and accuracies) and the computational performance (throughput and memory) of key algorithms, which are discussed in section 3. Finally, section 4 provides a few concluding remarks.

2. Algorithm Development

Some of the key TMD Battle Management algorithms are briefly discussed in this section. General purpose algorithms that are commonly used in a variety of areas are first presented, followed by a discussion of threat, sensor, and weapon models, and engagement planning and scheduling algorithms. A number of alternative algorithms were modeled and prototyped in most of the five areas discussed below, and disregarded in favor of the models presented in sections 2.1 - 2.5. The models presented here were chosen due to their balance in computational performance, engineering effectiveness and accuracies, while keeping them simple.

2.1 General Purpose Models

Mathematical Models

Solving Nonlinear Equations: To solve the fire control problem and to calculate interceptor firing tables (further discussed in section 2.4) require solving systems of nonlinear equations. The algorithm selected is the HYBRID subroutine of the MINPACK[1] software package, which employs a modified Powell hybrid method[2] iteratively calculating the solution by invoking a dogleg search algorithm[1, 3].

Solving Differential Equations: The fourth order Runge-Kutta-Gill method[4] of numerical integration is chosen for solving the differential equations of trajectory propagation.

Physical Models

Earth Gravity Model: The second order zonal harmonic expansion of the WGS-84 Earth Gravity Model[5] is used for trajectory propagation.

Earth Atmosphere Model: The 1976 U.S. Standard Atmosphere Model[6] is used for propagations.

Solving the Kepler Problem: The universal variable method[4] is used for solving the Kepler problem.

2.2 Threat Modeling

State Propagation

The algorithm for TBM state propagation in Earth Centered Earth Fixed coordinates employs the fourth order Runge-Kutta-Gill method to solve the differential equation of ballistic target dynamics involving the gravitational force, the drag acceleration, Coriolis and centrifugal accelerations.

Covariance Propagation

The Riccati equation is used to propagate the covariance matrix in a single step, and a first order approximation of the state transition matrix is used in solving it in Earth Centered Inertial coordinates.

Threat Monitoring

To avoid overloading the Battle Management system, track reports from the radar are re-propagated in the Battle Manager using the methods of the previous paragraphs, only when they

show significant variations from the previous state propagation. Thus, the variations on the ground impact point and time are determined by using efficient, approximate techniques such as first order Taylor expansions around the previous solutions as computed by the higher fidelity techniques of the earlier paragraphs.

2.3 Radar Modeling

The load on the radar is modeled to avoid saturating it by scheduling engagements too closely. A phased array radar is assumed, and the antenna occupancy is modeled as a key radar load measure. Occupancy is defined as the ratio of transmit and receive times to total time. In addition to occupancy, the track accuracy achievable by the radar is also modeled.

Search Occupancy

The contribution of occupancy due to searches is computed as follows: The number of beams to span the search volume is first computed; The pulse repetition interval (PRI) is then computed based on the maximum target velocity to fly through a beam; For a given cumulative probability of detection and number of looks, the single probability of detection is computed, and the corresponding signal-to-noise-ratio (SNR) determined; With this data, along with the minimum radar cross section (RCS), and the radar range equation, the pulselength is computed, which is then used to compute occupancy.

Object Occupancy

The occupancy due to radar activities other than search, including threat tracking and discrimination as well as interceptor tracking, are determined as follows: For a given object type, radar activity, and time interval, the PRI and desired SNR are determined based on specified radar parameters. The PRI, SNR, RCS, and the radar range equation are then used to compute the occupancy of each object.

Track Accuracy Prediction

To achieve successful intercepts, specific threat track accuracies need to be achieved by the radar that are within the divert capability of the interceptor. The computation of track accuracy takes into consideration the propagation of the error covariance matrix (computed by the technique described in section 2.2), and the performance of the radar, modeling the radar tracking filter for specified time-in-track and number of pulses. The latter is computed using the Sorensen approximation[7].

2.4 Weapon Modeling

In order for the Battle Manager to schedule engagements, it needs efficient methods to model the behavior of the weapon. The key problem in this area is to determine alternative fire control solutions. That is, solve the one-on-one weapon-target assignment problem. The fire control problem consists of finding firing parameters for a given intercept point and time. The solution to this problem entails weapon flyouts, which are typically intensive computations. To avoid throughput problems, some of the key computations are performed off-line, generating tables that are used in real-time.

Flyout Fans

Using a high fidelity 6-DOF trajectory generator modeling the weapon characteristics, numerous trajectories spanning the weapon kinematic reach are generated off-line using a specified granularity. As a result of these runs, the inputs (firing parameters) to the 6-DOF and the outputs (trajectory states) are stored as the Flyout Fans. Thus, for a given set of firing parameters, the flyout fan provides the corresponding trajectory states.

Firing Tables

The fire control problem consists of finding the firing parameters for a given trajectory state or intercept point, which is the inverse of the data provided by the flyout fans. However, using the flyout fan tables computed earlier, a fire control solution algorithm (using the Nonlinear Equation Solver described in section 2.1) computes firing parameters for a given intercept point. This computation is also performed off-line and the data stored in the Firing Tables. Thus, for a given intercept point, the firing tables provide the corresponding firing parameters.

Real-Time Computations

In real-time, the threat entry and exit points into the weapon's kinematic reach are first computed, which are then used to determine feasible alternate fire control solutions. This is accomplished by interpolating between the solutions stored in the firing tables. When a first-cut fire control solution is found using the firing tables, it is then used to obtain the corresponding weapon trajectory from the flyout fans to perform detailed constraint checking.

2.5 Engagement Planning and Scheduling

Engagement Planning and Scheduling is the core Battle Management problem. It consists of Threat Assessment, followed by Battle Space-Time Analysis, Weapon-Target Assignment (Engagement Planning), and Engagement Scheduling.

2.5.1 Threat Assessment

Threat Assessment determines if a target is threatening, and estimates the Total Damage Value that a given threat, if not intercepted, will incur upon the protected assets. The approach taken is probabilistic due to the system errors present, including track covariance and threat guidance error, rendering damage effects computations uncertain. Computations that are independent of actual track states are performed as part of preprocessing, while those dependent on track data are performed in real-time.

Preprocessing

Two sets of probabilities are computed off-line: the prior aim point probabilities and the conditional probability of damage to each asset. The prior aim point probability on each asset is computed as the probability of aiming at any asset weighted by the normalized value of the given asset. Given that the aim point is in an asset, the conditional probability of damage to another asset is computed by integrating over a Gaussian damage distribution.

Real-Time Processing

For a given threat state and covariance in real-time, unconditional posterior damage probabilities are computed for each asset, which are then multiplied with the value of the asset and summed over all assets to determine the expected total damage score for the given threat. Thus, when a track report is received from the radar in real-time, the size of the error covariance propagated to ground impact point (GIP) is compared to the threat's guidance error, and three cases are considered: Track covariance error compared to the threat's guidance error is a) very large, b) comparable, and c) very small.

a) Covariance Error Very Large

When the state error covariance is very large it provides almost no information as to where the aim point is intended. Consequently, the covariance information is disregarded in favor of the guidance error, and the posterior probability of aim point on each asset is approximated by the prior aim point probability for that asset. The unconditional probability of damage to a given asset is the sum over all assets of the product of the posterior probability of aim point on each asset and

the conditional probability of damage computed during pre-processing.

b) Covariance Comparable to Guidance Error

When the track error covariance is comparable to the TBM's guidance error, real-time processing is performed as follows: First, posterior aim point probabilities are determined by combining the prior aim point probabilities with the likelihood that the aim point is in a given asset for the specified GIP and covariance. The possible aim points are also adjusted in this step. Using these posterior aim point probabilities, the unconditional damage probabilities are computed as discussed in case 'a' above.

c) Covariance Error Very Small

When the track error covariance is sufficiently small compared to the TBM's guidance error, then the latter is disregarded, and the expected GIP is fairly localized. In this case, the unconditional posterior probabilities of damage are computed by integrating a Gaussian distribution centered at the GIP.

2.5.2 Battle Space-Time Analysis

The purpose of Battle Space-Time Analysis (BSTA) is to determine shot opportunities satisfying system constraints. BSTA trims a given threat timeline (from its launch time to ground impact time) and produces a feasible intercept time interval which satisfies all system constraints. Based on the feasible intercept intervals, BSTA also determines the rungs, that is, the shot opportunities. Finally, BSTA determines slack time, that is, the sliding intercept time interval without losing a rung.

To determine feasible intercept time intervals, system constraints are considered, including those due to specific weapons and sensors utilized. The following types of constraints are considered: kinematic constraints, such as minimum intercept altitude, weapon kinematic reach, and sensor field of view (FOV); weapon characteristics, including its time of flight (TOF), end game (seeker) requirements, and its lethality (single shot probability of kill) characteristics; radar constraints, including track accuracy, and avoidance of radiation sources. These constraints are engagement geometry dependent, hence are computed in real-time. An efficient search technique is used to compute the time intervals where each constraint is satisfied, and to find the intersection of these intervals which determine the feasible intercept interval satisfying all constraints.

2.5.3 Weapon-Target Assignment

Weapon-Target Assignment (WTA), or Engagement Planning, is the process of assigning defense resources in order to intercept attacking threats. The defense resources include both interceptors and radars. WTA uses the feasible intercept time intervals and the rung counts computed by BSTA, and the expected total damage score of each threat computed by threat assessment to assign defense resources. The objective is to minimize expected total damage score of all threats.

WTA operates globally on all threats considering shot opportunities during the current, or latest rung. The following steps are performed in WTA. First, launchers are assigned to minimize expected total damage score of all threats; Second, launcher assignments are modified to minimize interceptor inventory imbalance without significantly modifying the total damage score; Third, launchers are assigned to unassigned threats if any; Fourth, interceptors are reserved for later rungs; Fifth, when multiple sensors are available, they are assigned to minimize average occupancy imbalance. A number of assignment algorithms were considered, but the one considered most appropriate at this time for TMD Battle Management is the

Maximum Marginal Return[8] (MMR) algorithm. MMR is chosen due to its computational efficiency, since TMD Battle Management is algorithmically intensive and complex.

The assignment algorithm also considers different conditions such as TBM warhead type, the threatened asset characteristics, and the state of the battle.

2.5.4 Engagement Scheduling

While Engagement Planning or WTA, assigns defense resources to threats in a time independent fashion, Engagement Scheduling produces a detailed timeline of engagement events. Inputs to scheduling are: the assignments from WTA, as well as rung and slack times from BSTA. Within the time horizon under consideration, intercepts are scheduled as early as possible considering a number of constraints, including interceptor launcher rate constraint, and sensor occupancy.

Thus, a heuristic scheduling sequence is used: first shots of last rung (last shot opportunities), followed by upper rung shots, and finally, last rung follow-on shots if any. In each of these cases, shots are scheduled in increasing slack time, such that more constrained engagements are scheduled first. Also, engagements that can be supported by a single radar are scheduled first, followed by those that can be supported by multiple sensors. Finally, the radar occupancy constraint is considered by scheduling engagements as early as possible provided that total occupancy is below a specified threshold.

3. Prototyping and Simulation

The critical algorithms discussed in section 2, numbering over one hundred, were prototyped in Ada, tested, and integrated in a rapid prototyping testbed, consisting of over 30,000 source lines of code (SLOC).

Simulations were performed for a number of attack scenarios, assets to be protected, and defense laydowns. Attack scenarios consist of time tagged TBM tracks launched from a variety of enemy launch points, aimed at different assets, with a number of TBMs simultaneously in flight. The attack scenarios consist of different TBM types, some with longer ranges than others. The defended assets consist of point, area, and line assets. The defense laydown consists of a single radar and a collocated, single interceptor launcher site with multiple launchers. A number of defense laydowns were simulated and the effectiveness of the Battle Manager assessed.

Some of the simulation results are graphically represented in figures 1 - 12 for a particular attack scenario, assets to be protected, and defense laydown.

Figures 1 and 2 depict the attack scenario, with the targeting pairs represented by the first figure, while the second, represents a time snap shot of the TBMs in flight. Figures 3 and 4 depict the defense laydown, with the former representing the two-dimensional footprint of the radar FOV (the outer contour) and the footprint of the weapon kinematic reach (the inner contour). Figure 4 represents a radar search fence that provides detection of all threats.

The remaining diagrams, 5 - 12, present Battle Management results, emphasizing Engagement Planning and Scheduling algorithms. Figure 5 represents Threat Assessment, where track states and covariances as reported by the radar at a given time, are propagated by the Battle Manager to their GIPs, and their potential damage to assets determined (in this example, all targets are threatening). Figures 6 - 8 depict Battle Space-Time Analysis where three constraints are applied. Figure 6 slices the threat trajectories with the minimum keepout altitude of the weapon, such that the trajectory portions above the plane are eligible. Figure 7 overlays the radar FOV

to the previous constraint, such that trajectory portions within the cone are eligible. And Figure 8 applies the weapon kinematic reach constraint, where the trajectory portions within the volume are eligible for engagement. Figures 9 - 12 depict results of WTA and Engagement Scheduling. Figure 9 represents the timeline of a single threat, BSTA, and the scheduled shot taken in the upper rung represented by the dotted line. Figure 10 represents the results of WTA and Engagement Planning, performed simultaneously on all threats, depicting threat timelines, their rungs, and the scheduled shots. Figure 11 is a top down view of a snapshot of the battle as a result of Engagement Planning and Scheduling: threats attacking from the top of the diagram and interceptors countering from the bottom. Finally, for the particular example under consideration, Figure 12 depicts the results of Engagement Planning and Scheduling, with all threats successfully intercepted, some with a first shot, others with subsequent shots.

4. Conclusions

This is one of the first attempts to analyze the whole TMD Battle Management problem in an integrated fashion. It has been modeled, prototyped and simulated under various conditions. Some of the key results of this analysis have been graphically presented. The algorithms developed have been demonstrated to be fairly effective against postulated scenarios. The key driver for overall weapon system effectiveness seems to be BSTA, which depends on satisfying constraints that are independent of real-time Battle Management. Further analysis is required to simulate results of defense laydowns with multiple radars and launcher sites, and in some cases, the effectiveness of higher fidelity models.

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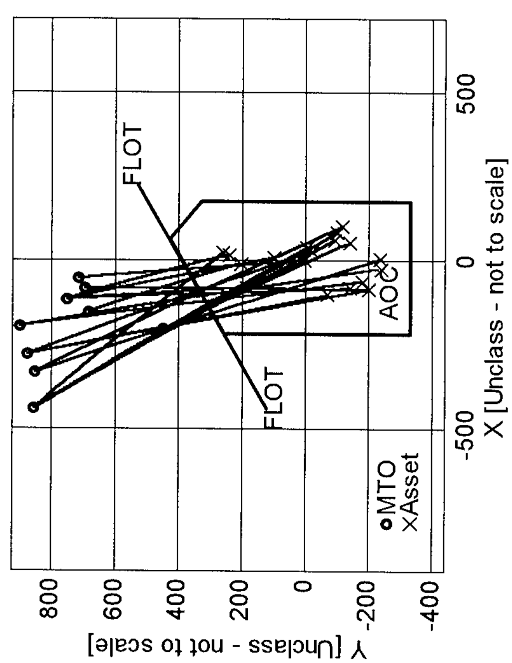

Figure 1: 2D Targeting Pairs

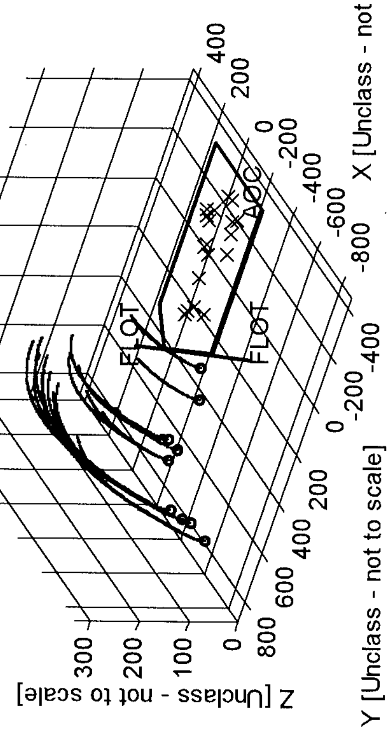

Figure 2: 3D Attack Scenario

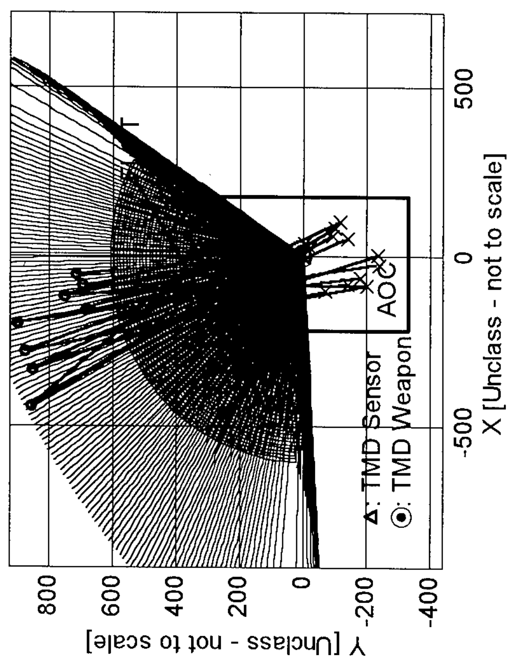

Figure 3: 2D Defense Laydown

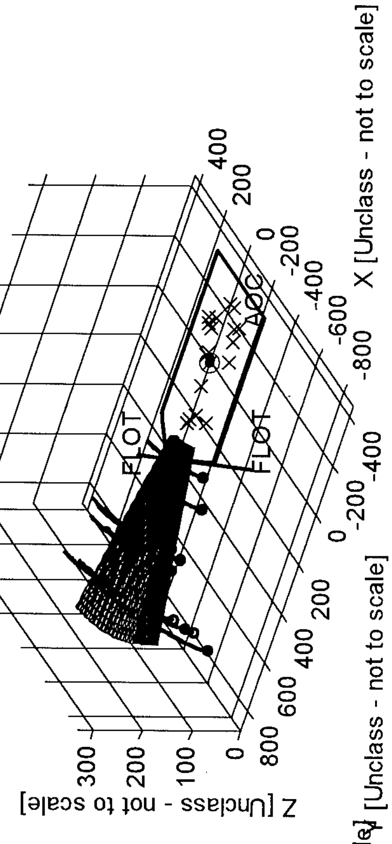

Figure 4: TMD Sensor Search Fence

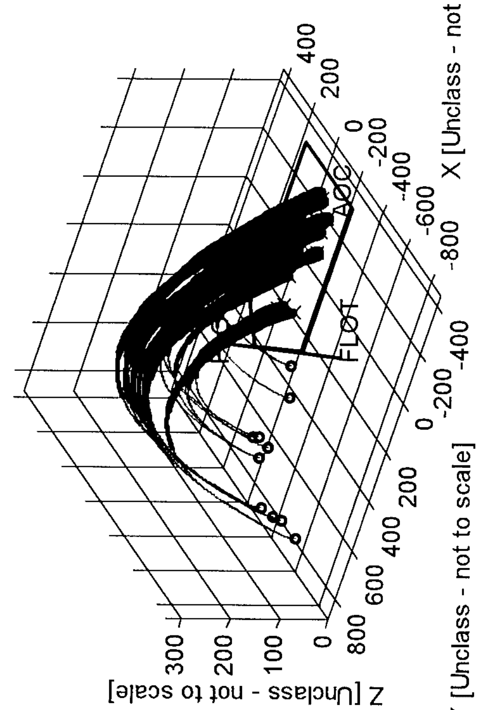

Figure 5: Track Propagation and Threat Assessment

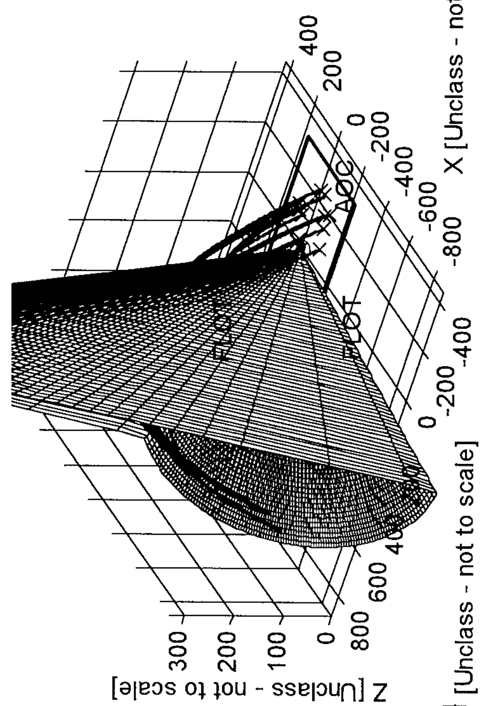

Figure 7: BSTA - TMD Sensor FOV

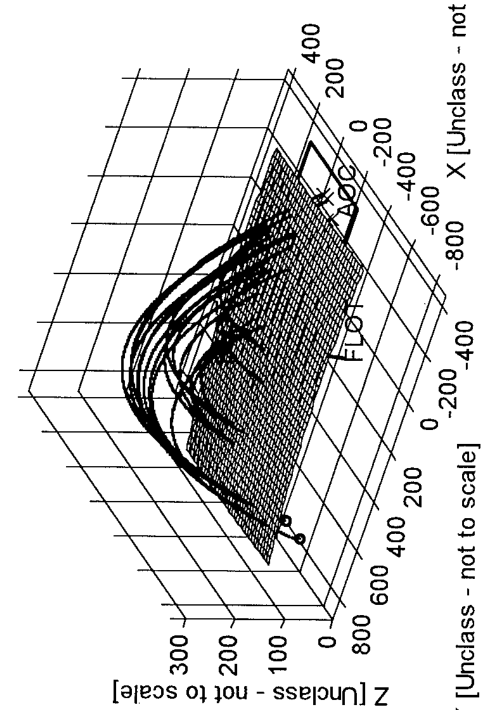

Figure 6: BSTA - Upper Tier Weapon System Keepout Altitude

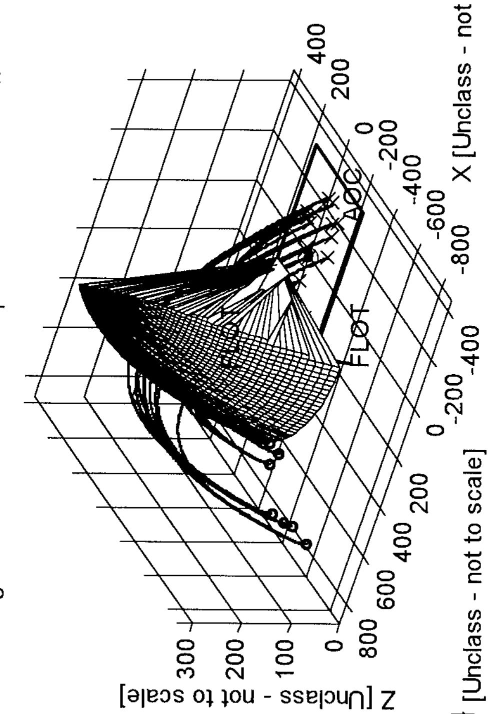

Figure 8: BSTA - TMD Weapon Kinematic Reach

Figure 9: Single Threat Timeline and Scheduled Intercept

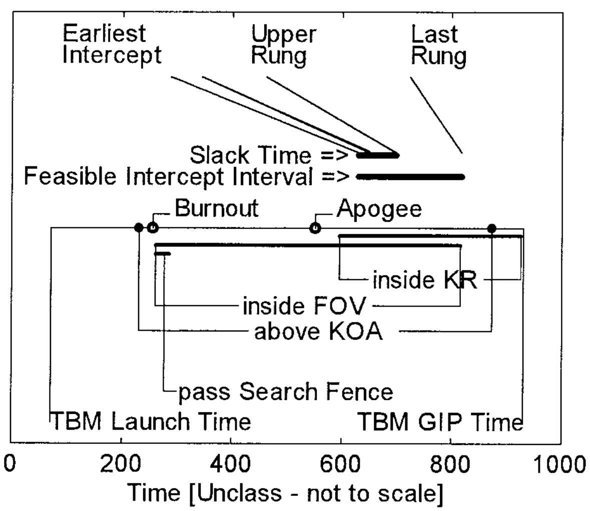

Figure 11: 2D Engagement Scenario

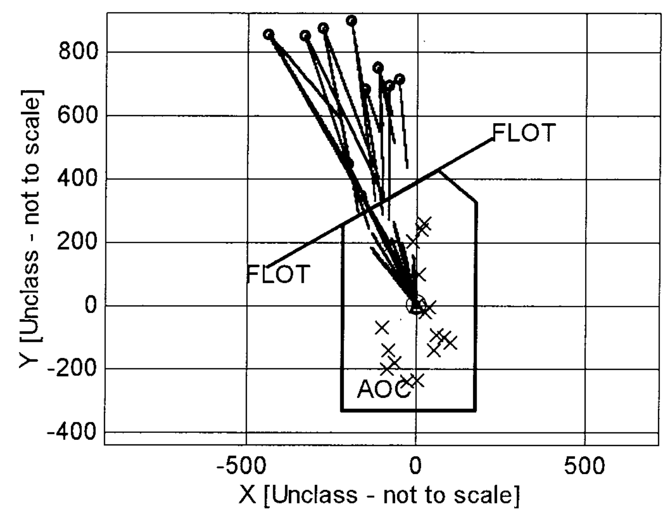

Figure 10: All Threats Planned/Scheduled Engagement

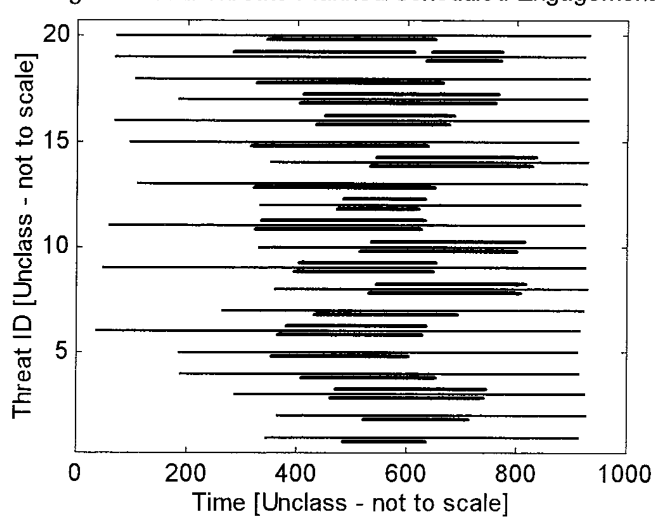

Figure 12: 3D Engagement Scenario